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# Reduction of the intersubband scattering delta doped layers by the Lorentz-force of an in-plane magnetic field

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**Abstract.** In structures with a narrow delta doped layer we observe a strong anisotropy in the magnetoresistance when the current is applied either parallel or perpendicular to the in-plane magnetic field. This anisotropy is absent in structures with thick doping layers. By a detailed analysis of the solution of the Boltzmann transport equation we were able to show that the anisotropy is due to a reduction in the intersubband scattering. The reduction of the intersubband scattering is due to the fact that the Lorentz-force pushes electrons, which move perpendicular to the in-plane magnetic field direction, away from the layer of ionized impurities.

## Introduction

The diamagnetic shift is well known to give rise to subband depopulation when an in-plane magnetic field is applied to a 2D system with more than a single subband occupied. The depopulation of a subband leads to so-called diamagnetic Shubnikov–de Haas oscillations that are observable in the magnetoresistance. Already in 1986 Reisinger and Koch [1] calculated a universal depopulation diagram for delta doped structures. This diagram predicts the magnetic field value at which the depopulation of a subband will occur. By now the R & K diagram has become the standard for the study of depopulation effects in delta doped structures in many III/V semiconductors. It has however never been tested in the high magnetic limit where we can expect the depletion of the first excited subband.

## 1 Experiments

Using pulsed magnetic fields up to 50 T we have studied in detail the validity of the R&K diagram for GaAs structures with single and coupled delta doped layers. When the current is applied either parallel or perpendicular to the in-plane magnetic field we observe a strong anisotropy for the depopulation of the $n = 1$ subband in structures with a single narrow delta doped layer, see Fig. 1(a). This anisotropy is absent in structures with a thick doping layer, see Fig. 1(b). The dependence of the anisotropy on the layer thickness is observed in samples with a higher doping concentration. A similar effect is also observed for coupled delta doped layers where we find a strong anisotropy when the delta layers are strongly coupled but where the anisotropy disappears when the coupling between the layers becomes weaker.

For a large number of samples with a narrow doping profile, i.e. a width of 2 nm, we have determined the inflection point on the negative slope of the diamagnetic Shubnikov–de Haas oscillations. Normally this inflection point is considered to coincide with the magnetic depopulation. As is shown in Fig. 2 the deviation from the calculated values can be quite large and the apparent depopulation of the $n = 1$ subband seems to depend on the orientation of the current with respect to the magnetic field.

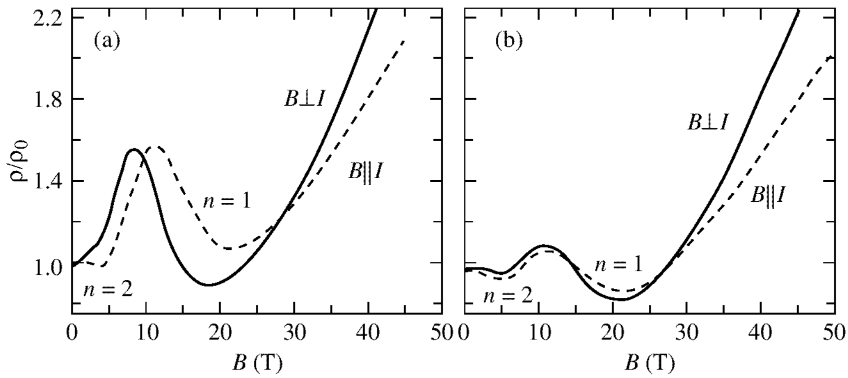


**Fig. 1.** Diamagnetic Shubnikov–de Haas oscillations measured in a sample with a narrow doping profile (a) and a thick doping profile (b). The current is applied either parallel or perpendicular to the in-plane magnetic field. The doping density is $2 \times 10^{12}$ cm$^{-2}$ for both samples. The sample in (a) has a width of the doping layer of 2 nm whereas the width of the sample in (b) is close to 6 nm.

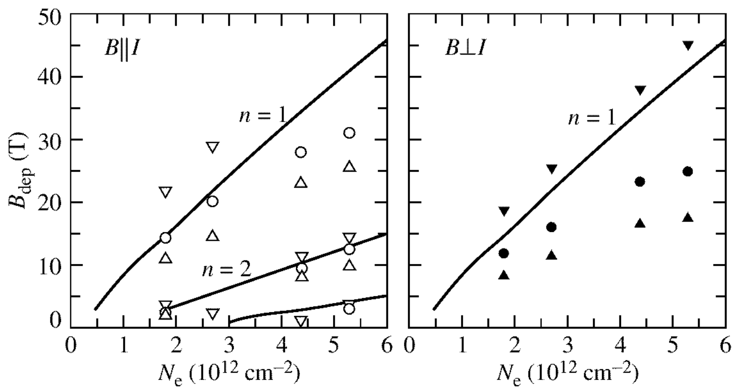


**Fig. 2.** Comparison of the minimum (▽), inflection point (○) and the maximum (△) in the diamagnetic Shubnikov–de Haas oscillations measured in samples with a narrow doping profile. The current is applied either parallel (a) or perpendicular (b) to the in-plane magnetic field.

## 2 Analysis and discussion

We have solved the Boltzmann-transport equation in order to calculate the transverse and longitudinal magnetoresistivity components, i.e. the current perpendicular or parallel to the in-plane magnetic field. The calculation of these magnetoresistivity components is rather complicated as we have to deal with anisotropic Fermi-contours, a finite number of occupied and empty subbands, etc. The calculations show that a depopulation is observable in the magnetoresistivity by a drop in the resistivity because the intersubband scattering disappears when the Fermi energy drops below the $n = 1$ subband. Similar results for a heterostructure were obtained by Ensslin *et al.* [2]. Our detailed analysis showed that the observed anisotropy and the deviation of the observed depopulation field value from the R&K value is due to a strong reduction of the intersubband scattering previous to the actual crossing of the Fermi-energy with the bottom of the $n = 1$ subband. The reduction of the intersubband scattering turns out to be due a Lorentz force induced shift of the wavefunction when the in-plane magnetic field is applied perpendicular to the movement of the electrons.

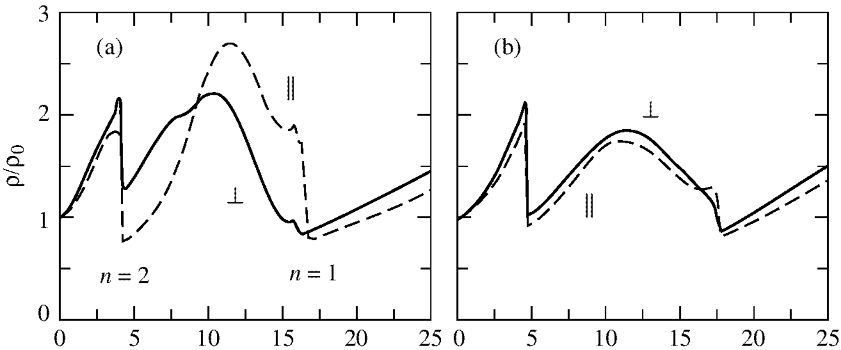


**Fig. 3.** Calculated diamagnetic Shubnikov–de Haas oscillations for a structure with single delta doped layer of (a) 2 nm and (b) 10 nm thick. The calculations are normalized by the magnetoresistance at zero magnetic field.

Due to this shift the overlap between the wavefunction of the $n = 1$ subband and the layer of ionized impurities is strongly reduced. This strong reduction in the overlap gives rise to a near complete annihilation of the intersubband scattering between the two lowest subbands. This mechanism only works in structures that have a narrow distribution of the ionized impurities. As is shown in Fig. 3 the numerically obtained magnetoresistivity curves agree nicely with the experimentally observed curves in structures with different doping layer thicknesses. In structures with a narrow doping profile the anisotropy is large whereas it is almost absent in structures with a thick doping profile. Similar results where obtained in structures with different separations between two coupled delta layers.

## 3 Conclusions

In structures with delta doped layers we measured the longitudinal and transversal magnetoresistance.when an in-plane magnetic field is applied. We observed a strong anisotropy for these two components of the magnetoresistance in structures with single narrow doped layers or in structures with strongly coupled delta doped layers. The apparent depopulation that is determined from the diamagnetic Shubnikov–de Haas oscillations also deviates from the theorectical predicted values in these structures. All these effects are mainly due to a Lorentz force induced shift of the wavefunction when an electron moves perpendicular to the in-plane magnetic field direction.

## References


[1] H. Reisinger and F. Koch, *Surf. Sci.* **170**, 397 (1986).

[2] K. Ensslin, A. Wixford, M. Sundaram, P. F. Hopkins, J. H. English and A. C. Gossard, *Phys. Rev. B* **47**, 1366 (1993).